

Decaying Vector Dark Matter as an Explanation for the 3.5 keV Line from Galaxy Clusters

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Abstract

We present a Vector Dark Matter (VDM) model that explains the 3.5 keV line recently observed in the XMM-Newton observatory data from galaxy clusters. In this model, dark matter is composed of two vector bosons, V and V' , which couple to the photon through an effective generalized Chern-Simons coupling, g_V . V' is slightly heavier than V with a mass splitting $m_{V'} - m_V \simeq 3.5$ keV. The decay of V' to V and a photon gives rise to the 3.5 keV line. The production of V and V' takes place in the early universe within the freeze-in framework through the effective g_V coupling when $m_{V'} < T < \Lambda$, Λ being the cut-off above which the effective g_V coupling is not valid. We introduce a high energy model that gives rise to the g_V coupling at low energies. To do this, V and V' are promoted to gauge bosons of spontaneously broken new $U(1)_V$ and $U(1)_{V'}$ gauge symmetries, respectively. The high energy sector includes milli-charged chiral fermions that lead to the g_V coupling at low energy via triangle diagrams.

1 Introduction

Although strong hints for the existence of a form of Dark Matter (DM) consisting above 25 % of the whole energy density of the Universe is established,

our knowledge on properties of the particles making up the DM is very limited. In particular, we still do not know the values of DM mass, spin and lifetime. We do not also know whether DM consists of a single sort of particle or like ordinary matter comes in varieties of elementary and composed particles. There is a rich literature suggesting candidates for DM but most of them focus on the simplest scenario with a single stable DM candidate with mass of $O(100 \text{ GeV})$ and with spin equal to 0 or $1/2$. Possibility of DM with spin one (*i.e.*, vector DM) has been only recently attracted attention [1, 2].

Recently Ref. [3] has found a photon line at energy of $(3.55 - 3.57) \pm 0.03 \text{ keV}$ at more than 3σ C.L. in the data collected by XMM-Newton observatory from 73 galaxy clusters distributed in redshifts between 0.01-0.35. The Chandra data on Perseus also confirms this result [3]. Ref. [3] carefully analyzes the possibility of interpreting this line as an atomic transition line but according to [3] such an interpretation does not seem to be likely within the standard picture (see however, Ref. [4]). Moreover no 3.5 keV signal has been found from Virgo. An independent analysis in Ref. [5] finds a similar signal from Andromeda galaxy and Perseus cluster. One explanation is decaying DM to a photon. Assuming that most of dark matter today is composed of one form of decaying particle, in order to explain the intensity of the line, the lifetime has to be [5]

$$\tau_{DM} = 10^{28} - 10^{29} \text{ sec} \frac{7 \text{ keV}}{m_{DM}}. \quad (1)$$

However, one should bear in mind that atomic line emission is not conclusively ruled out [3, 4]. Conclusive results can be achieved after analysis of Astro-H data [3, 5]. Moreover, according to [6] the Chandra X-ray observations of the Milky Way are consistent with the line at 3.5 keV line only with most conservative assumptions on astrophysical sources (see, however, Ref. [7]). Ref [8] investigates the presence of the line in the stacked spectra of dwarf spheroidal galaxies and finds no signal. Under standard assumption on the galactic dark matter column density, the null signal excludes the dark matter origin of the 3.5 keV line at 4.6σ C.L. However as pointed out in [8], Ref [3] does not include the foreground dark matter halo of the milky way itself. Inclusion of this foreground will alleviate the tension between the two results. Considering such debates, it is still premature to claim a solid observation of the line. Nevertheless, there is already rich literature trying to present a model explaining the line by DM decay [9], annihilation [10] or axion-like DM conversion [11]. Ref. [12] suggests a dark matter model that

explains the line by atomic hyperfine transitions in dark atoms.

In the present paper, we propose a scenario in which dark matter is composed of two vector bosons V and V' with $m_{V'} - m_V \simeq 3.5$ keV. V' is metastable and decays into V and a photon comprising the 3.5 keV line. The other boson V is protected against decay by a Z_2 symmetry. The decay of V' proceeds via a generalized Chern-Simons interaction term of form

$$g_V \epsilon^{\alpha\beta\mu\nu} F_{\alpha\beta} V_\mu V'_\nu . \quad (2)$$

This is an effective coupling valid below cut-off Λ . The same interaction can lead to the observed amount of DM abundance within the freeze-in framework while $m_{V'} < T < \Lambda$ via s -channel $f\bar{f} \rightarrow \gamma^* \rightarrow VV'$. We introduce a high energy model that includes (milli-)charged chiral fermions with heavy masses that lead to the effective coupling in (2) through a triangle diagram.

We introduce the dark matter model in section 2 and a UV-completion for the scenario in section 3. Conclusions are summarized in section 4.

2 The scenario

In this section, we show that the $V' \rightarrow \gamma V$ decay via the generalized Chern-Simons coupling in Eq. (2) can explain the claimed 3.5 keV line. We then show that the same coupling can lead to V and V' production in the early universe with desired abundance within the freeze-in framework.

In [2], we proposed a vector DM model with mass of 130 GeV and a generalized Chern-Simons coupling to explain the 130 GeV line that had been back then claimed to be observed in the Fermi-LAT data from galaxy center [13]. It is tantalizing to invoke similar scenario to explain the 3.5 keV line via t -channel annihilation of a pair of vector DM with mass of 3.5 keV to a photon pair. To account for the intensity [14], $g_V/m_{V'}$ should be $\sim (0.18 - 0.38)\text{GeV}^{-1}$. Such values of parameters lead to too large monophoton plus missing energy signal at the LHC via $f\bar{f} \rightarrow VV'$ and subsequently $V' \rightarrow V\gamma$ [2]. The bound from LHC rules out this scenario [15]^a.

^aUsing the eXcited Dark Matter mechanism (XDM) is another possibility to explain the X-ray line [16]. Within the XDM scenarios, dark matter particles can be up-scattered to the heavier state V' via $\langle \sigma(VV \rightarrow V'V')v \rangle \sim 6 \times 10^{-6} (g_V^4/m_V^2) (v/2000 \text{ km/sec})$. The 3.5 keV X-ray line can be subsequently produced by $V' \rightarrow V\gamma$, provided that $m_{V'} - m_V \simeq 3.5$ keV. Using the results of [16] and equating the predicted and observed flux from Perseus, we find that $g_V/m_V \sim 1 \text{ GeV}^{-1}$. Such values of parameters are already ruled out by VV'

Let us now take

$$m_{V'} - m_V \simeq 3.5 \text{ keV} \ll m_{V'} . \quad (3)$$

Moreover, let us suppose that both V and V' have been produced in the early universe. The decay of non-relativistic V' will then lead to 3.5 keV line. In order to explain the intensity, relation Eq. (1) should be satisfied. As shown in [2], the decay rate is given by:

$$\Gamma(V' \longrightarrow V + \gamma) = \frac{g_V^2 \cos^2 \theta_W}{24 \pi} \frac{(m_{V'}^2 - m_V^2)^3 (m_{V'}^2 + m_V^2)}{m_V^2 m_{V'}^5}.$$

Assuming that the densities of V and V' are equal today, the lifetime of V' should be half what is shown in Eq. (1) to account for the observed intensity of the 3.5 keV line. Thus, we find:

$$g_V \simeq (5 \times 10^{-16} - 1.5 \times 10^{-15})(m_V/\text{GeV})^{3/2} . \quad (4)$$

This coupling is too small to lead to observable effects at collider experiments. Through the generalized Chern-simons coupling, the dark matter can interact inelastically with nuclei via a t -channel photon exchange [2, 17]. Taking $m_{V'} - m_V \simeq 3.5 \text{ keV}$, for $m_V = 30 \text{ GeV}$, we find that the DM-nucleon cross section should be smaller than $6.2 \times 10^{-53} \text{ cm}^2$ which is well below the bound from LUX [18].

The production of V and V' will take place via $f\bar{f} \rightarrow \gamma^* \rightarrow VV'$ at low temperatures $T < \Lambda$ where effective g_V coupling is valid and Λ is the cutoff above which the effective g_V coupling is not valid. In [2], the cross section of $f\bar{f} \rightarrow \gamma^* \rightarrow VV'$ is calculated:

$$\sigma(f\bar{f} \rightarrow VV') = \frac{(eg_V Q_f \cos \theta_W)^2}{12\pi N_c E_{cm}^6 m_V^2 m_{V'}^2} \mathcal{K} \mathcal{S}(E_{cm}, m_V, m_{V'}) \quad (5)$$

where $\mathcal{K} = \sqrt{(E_{cm}^2 + m_V^2 - m_{V'}^2)^2 - 4m_V^2 E_{cm}^2}$ and

$$\mathcal{S}(E_{cm}, m_V, m_{V'}) = [E_{cm}^4 + (m_V^2 - m_{V'}^2)^2](m_V^2 + m_{V'}^2) - 2E_{cm}^2(m_V^4 - 4m_V^2 m_{V'}^2 + m_{V'}^4).$$

Notice that as $E_{cm} \rightarrow \infty$, the production cross section converges to a constant value. This behavior reflects the fact that g_V is valid only below $E_{cm} \lesssim \Lambda$.

pair production in colliders as well as absence of the monochromatic photon line at $E = m_V$ from dark matter annihilation via $\langle \sigma(VV \rightarrow \gamma\gamma)v \rangle \sim 0.03 m_V^{-2} \sim 12 \mu b (\text{GeV}/m_V)^2$.

Because of this behavior, most of VV' production will take place at high temperatures when $T \gg m_V$. Using the formulations for freeze-in framework developed in [19] we find

$$(\Omega_V + \Omega_{V'})h^2 \simeq 1.5 \times 10^{22} g_V^2 \frac{T_f}{m_V}$$

where we have set the upper bound of integration on temperature equal to T_f . If the reheating temperature is smaller than Λ , we should set $T = T_R$; otherwise, we should set $T_f = \Lambda$. Inserting $g_V^2 \sim 10^{-30} m_V^3/\text{GeV}^3$ and setting $\Omega_{DM}h^2 = (\Omega_V + \Omega_{V'})h^2 = 0.1$, we obtain

$$T_f \simeq 7 \times 10^6 \text{ GeV} \left(\frac{\text{GeV}}{m_V} \right)^2 \left(\frac{10^{-15}}{g_V} \right)^2. \quad (6)$$

Notice that the results depend on the upper bound of integration on temperature, T_f . This is not unexpected within freeze-in framework. We should however study the high energy model that leads to the effective g_V coupling in low temperatures to make sure that at higher temperatures, there is no mechanism to overproduce DM. This will be done in the next section.

3 Ultraviolet completion of the scenario

In the previous sections, we focused on low energies and temperatures at which the couplings of vector bosons V and V' to SM is through the generalized Chern-Simons coupling, g_V . As we discussed earlier, the g_V coupling is an effective coupling valid only below a certain energy scale. In this section, we try to first introduce a UV-completed model that, below a certain energy scale, yields the effective coupling in Eq. (2). We then estimate the abundance of V and V' produced in the early universe at temperatures above the cut-off of the effective coupling. As shown in [20], generalized Chern-Simons coupling can result from triangle diagram in which chiral fermions propagate. The interesting point is that g_V turns out to be independent of the masses of these particles. In the following, we assume that V and V' are gauge bosons of new $U_V(1)$ and $U_{V'}(1)$ symmetries and acquire mass via Higgs mechanism. We moreover add Dirac fermions ψ_i which are colorless and singlet under electroweak $SU(2)$ but have nonzero hypercharge and therefore nonzero electric charge. The new fermions are also taken to be in doublet representations of

$U_V(1)$ and $U_{V'}(1)$. That is under $U_V(1)$

$$\psi_{iR} \xrightarrow{U_V(1)} e^{iQ_{iR}\sigma_1} \psi_{iR} \quad \text{and} \quad \psi_{iL} \xrightarrow{U_V(1)} e^{iQ_{iL}\sigma_1} \psi_{iL}$$

and under $U_{V'}(1)$

$$\psi_{iR} \xrightarrow{U_{V'}(1)} e^{iQ'_{iR}\sigma_1} \psi_{iR} \quad \text{and} \quad \psi_{iL} \xrightarrow{U_{V'}(1)} e^{iQ'_{iL}\sigma_1} \psi_{iL},$$

where σ_1 is the two by two Pauli matrix. The reason we choose doublet representation is to maintain the Z_2 symmetry that prevents V and V' from mixing with photon. We will return to this point later. The Lagrangian of the fermions can be written as

$$\mathcal{L}_\psi = \sum_i \left[\bar{\psi}_{iL} i \not{D} \psi_{iL} + \bar{\psi}_{iR} i \not{D} \psi_{iR} + (Y_i \psi_{iR}^\dagger \Delta_i \psi_{iL} + H.c.) \right], \quad (7)$$

where $D_\mu = \partial_\mu - ie_V Q_i V_\mu \sigma_1 - ie'_V Q'_i V'_\mu \sigma_1 - ie q_i B_\mu / \cos \theta_W$. The fields Δ_i are two by two matrices of scalars which are electrically neutral and transform under new gauge symmetries as follows:

$$\Delta_i \xrightarrow{U_V(1)} e^{iQ_{iR}\sigma_1} \Delta_i e^{-iQ_{iL}\sigma_1} \quad \text{and} \quad \Delta_i \xrightarrow{U_{V'}(1)} e^{iQ'_{iR}\sigma_1} \Delta_i e^{-iQ'_{iL}\sigma_1}. \quad (8)$$

Let us take the potential of Δ_i as follows

$$\begin{aligned} V(\Delta_i) = & -m_{\Delta_i}^2 \text{Tr}[\Delta_i^\dagger \Delta_i] - m_{\Delta_i}^2 \text{Tr}[\Delta_i^\dagger \sigma_1 \Delta_i \sigma_1] + \lambda (\text{Tr}[\Delta_i^\dagger \Delta_i])^2 \\ & + \lambda_1 \left| \text{Tr}[\Delta_i^\dagger \Delta_i \sigma_1] \right|^2 + \lambda_2 \left| \text{Tr}[\Delta_i \Delta_i^\dagger \sigma_1] \right|^2. \end{aligned} \quad (9)$$

It is straightforward to show that $V(\Delta_i)$ is invariant under any

$$\Delta_i \rightarrow e^{i\alpha_i \sigma_1} \Delta_i e^{i\beta_i \sigma_1}. \quad (10)$$

Notice that transformations in Eq. (8) are a subgroup of transformations in Eq. (10). The potential in Eq. (9) is not the most general potential invariant under (10). Combinations such as $\text{Tr}[\Delta_i^\dagger \Delta_i \sigma_1]$ also respect (10). Our aim here is not to write down the most general Lagrangian. On the contrary we want to write a simple Lagrangian that breaks $U_V(1) \times U_{V'}(1)$ in a desired way maintaining the Z_2 symmetry that guarantees the stability of V

and the meta-stability of V' and gives the same mass to the two components of ψ_{iL} doublets. It is straightforward to verify that

$$\langle \Delta_i \rangle = \begin{bmatrix} v_i & 0 \\ 0 & v_i \end{bmatrix} \quad (11)$$

is a minimum of the potential in Eq. (9) and any other minimum can be transformed to this form by employing transformations (10). From now on, we will work in this basis. Notice that the two components of ψ_i are degenerate with masses

$$m_{\psi_i} = Y_i v_i. \quad (12)$$

Moreover the Lagrangian respects a Z_2 symmetry under which V_μ, V'_μ , second component of ψ_i , $(\Delta_i)_{12}$ and $(\Delta_i)_{21}$ are odd but the rest of fields are even. This Z_2 symmetry stabilizes the V boson. Vacuum expectation values of Δ_i spontaneously break $U_V(1)$ and $U_{V'}(1)$ and induce mass terms for V_μ and V'_μ . We will discuss this after fixing the charges.

	ψ_{1L}	ψ_{1R}	ψ_{2L}	ψ_{2R}
$U_V(1)$	1	-1	1	1
$U_{V'}(1)$	1	1	-1	1
$U_{em}(1)$	q	q	q	q

Table 1: $U(1)$ charges of new fermions.

Like the case of the standard model Z boson, we can choose a gauge that V and V' have three degrees of freedom including longitudinal components. Notice that masses of ψ_i come from Yukawa couplings with Δ_i which are electroweak $SU(2)$ singlets. Since they develop VEV, they have to be electrically neutral. As a result, hypercharges of ψ_{iL} and ψ_{iR} should be equal. This automatically cancels out all anomalies of the $SU(3) \times SU(2) \times U(1)$ gauge group of standard model. Anomalies of $U_V(1) \times U_{V'}(1)$ symmetries also cancel because we have chosen the doublet representation and $\text{Tr}[\sigma_1 \sigma_1 \sigma_1] = 0$. As shown in [20], the effective coupling can be written as

$$g_V = \frac{ee_V e'_V}{48\pi^2} \sum_i (Q_{iL} Q'_{iR} - Q_{iR} Q'_{iL}) q_i. \quad (13)$$

Notice that as long as the two components of the ψ_i doublets are degenerate, the amplitude of triangle diagram contributing to g_V in which these two

components propagate is equal to what calculated in [20] for fermions in singlet representation of $U(1)$. The only difference is that for each doublet the contribution to g_V should be doubled because there are two equal triangle diagrams corresponding to the case that either of two components couple to the photon. The combination of the charges in Eq. (13) has to be nonzero; however, from anomaly cancelation we find that certain other combinations of the charges must vanish:

(1) Cancelation of the $U_V(1) - U_V(1) - U_{em}(1)$ anomaly implies

$$\sum_i (Q_{iL}^2 - Q_{iR}^2) q_i = 0.$$

(2) Similarly, cancelation of the $U_{V'}(1) - U_{V'}(1) - U_{em}(1)$ anomaly implies

$$\sum_i (Q'_{iL}{}^2 - Q'_{iR}{}^2) q_i = 0;$$

(3) Finally, cancelation of the $U_V(1) - U_{V'}(1) - U_{em}(1)$ anomaly implies

$$\sum_i (Q'_{iL} Q_{iL} - Q_{iR} Q_{iR}) q_i = 0.$$

Satisfying all these conditions and obtaining a nonzero g_V is not a trivial problem. In fact, it is straightforward to show that with only a single ψ_i this cannot be done and to obtain a nonzero g_V in a anomaly free theory, the number of ψ_i has to be increased at least to two. In table 1, we show an assignment of charges for two fermions ψ_1 and ψ_2 that satisfies all these conditions.

VEVs of Δ_1 and Δ_2 will induce masses for V and V' . In general, a tree level mass mixing between V and V' can appear but with charge assignment that we have chosen, no mixing between V and V' appears. The gauge bosons obtain masses as follows

$$m_V = 2e_V v_1 \quad \text{and} \quad m_{V'} = 2e'_V v_2. \quad (14)$$

To explain the quasi-degeneracy of V and V' , we can impose an approximate exchange symmetry on $V(\Delta)$ under $\Delta_1 \leftrightarrow \Delta_2$. This exchange symmetry can be softly broken by m_Δ^2 terms.

Notice that ψ_1 and ψ_2 having different quantum numbers cannot mix before breaking $U_V(1)$ and $U_{V'}(1)$. Vacuum Expectation Values (VEV) of

Δ_1 and Δ_2 however break $U_V(1)$ and $U_{V'}(1)$, respectively. In principle, mass terms of $\psi_{1R}^T c \Delta_2 \psi_{2R}$ and $\psi_{1L}^T c \Delta_1 \psi_{2L}$ can mix these two. We can however forbid such terms by imposing a new flavor symmetry under which $\psi_1 \rightarrow \psi_1$ and $\psi_2 \rightarrow -\psi_2$. In general, Eq. (7) induces V and V' mixing at one loop level. However, as long as we forbid ψ_1 and ψ_2 mixing, with particular charge assignment shown in table, no mixing between V and V' appears at loop level. This can be observed by rewriting gauge couplings of ψ_1 and ψ_2 in Eq. (7) for charge assignments in table as follows

$$(e_V \bar{\psi}_1 \gamma^\mu \gamma^5 \sigma_1 \psi_1 V_\mu + e_{V'} \bar{\psi}_1 \gamma^\mu \sigma_1 \psi_1 V'_\mu) + (e_V \bar{\psi}_2 \gamma^\mu \sigma_1 \psi_2 V_\mu + e_{V'} \bar{\psi}_2 \gamma^\mu \gamma^5 \sigma_1 \psi_2 V'_\mu). \quad (15)$$

If we forbid the mixing of ψ_1 and ψ_2 as well as the mixing of Δ_1 and Δ_2 , the loops will involve either ψ_1 or ψ_2 . As long as only ψ_1 is involved we take V and V' respectively C-odd and C-even so the $V - V'$ mixing will be forbidden by charge conjugation symmetry. The operator $\epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} V_\alpha V'_\beta$ is however invariant under charge conjugation and will be therefore allowed.

So far we have not determined the value of the electric charge of new fermions. In principle, like the millicharge scenario [21], q can be much smaller than 1. Under global transformations $\psi_1 \rightarrow e^{i\alpha_1} \psi_1$ and $\psi_2 \rightarrow e^{i\alpha_2} \psi_2$, the Lagrangian in Eq. (7) is invariant. This global $U(1) \times U(1)$ symmetry protects ψ_1 and ψ_2 from decay. If ψ_1 and ψ_2 are not produced in the first place, they cannot contribute to the DM abundance. Moreover they cannot lead to production of V_μ and V'_μ via $\bar{\psi}_i \psi_i \rightarrow V^{(\prime)} V^{(\prime)}$. The following two regimes can be distinguished:

- $T_R < m_\psi$: Obviously, if the reheating temperature is below m_ψ , these fermions cannot be produced. The electric charge of ψ_i , q , can take any value in the perturbative range. Moreover, we should set T_f in Eq. (6) equal to T_R . From Eqs. (12,13,14), we therefore find

$$m_V \gtrsim 2 \text{ GeV} q^{-2/9} (10^{-15}/g_V)^{-8/9} Y^{-4/9}.$$

Taking $g_V = 10^{-15} (m_V/\text{GeV})^{3/2}$, we obtain $m_V > 1.5 \text{ GeV} q^{-2/21} Y^{-4/21}$ and $T_R = T_f < 10^6 \text{ GeV} q^{10/21} Y^{20/21}$. Taking $m_\psi > T_R > \text{TeV}$, we find $q Y^2 > 5 \times 10^{-7}$.

- $T_R > m_\psi$: In this case, q should be small enough not to lead to production of ψ_1 and ψ_2 in the early universe. Taking the production rate

in the early universe to be of order of $\Gamma_\psi \sim e^4 q^4 T / (4\pi)$, we find that as long as

$$eq < 4 \times 10^{-5} (m_\psi / \text{GeV})^{1/4}, \quad (16)$$

the production of ψ in the early universe is negligible^b (*i.e.*, $\Gamma_\psi H|_{T=m_\psi} \ll 1$). As discussed before, T_f in Eq (6) should be set equal to $\Lambda = m_{\psi_i} = v_i Y_i$. From Eqs. (12,13,14,16), we therefore find

$$m_V > 7 \text{ GeV} (g_V / 10^{-15})^{-3/8} Y^{-1/2}.$$

Taking $g_V \simeq 10^{-15} (m_V / \text{GeV})^{3/2}$, we find $m_V > 3.5 \text{ GeV} Y^{-8/25}$ and $m_\psi \sim T_f = 13 \text{ TeV}$ and therefore $q < 10^{-3}$. The reheating temperature can have any value above 14 TeV which is consistent with the canonical picture.

4 Conclusions

We have presented a dark matter model explaining the 3.5 keV line observed in the XMM-Newton observatory data on galaxy clusters. The model is composed of a light and a heavy sector with a large mass gap of more than four orders of magnitudes. The light sector includes two vector bosons V_μ and V'_μ which play the role of the dark matter. The model respects a Z_2 symmetry under which standard model particles are even but V and V' are odd. V , being the lightest Z_2 -odd particle, is stabilized by the Z_2 symmetry. These two vectors couple to the photon via a generalized Chern-Simons coupling, g_V . Through this coupling, V' can decay to V and a photon comprising the 3.5 keV line. The intensity of the line determines the value of the g_V coupling: $g_V \simeq 10^{-15} (m_V / \text{GeV})^{3/2}$. Such a small coupling cannot lead to an observable signal in the dark matter direct detection experiments or at colliders in any foreseeable future. The same coupling can however produce enough DM in the early universe via $f\bar{f} \rightarrow \gamma^* \rightarrow VV'$ within freeze-in mechanism. The production is most efficient at higher temperatures. That is because for energies much larger than $m_{V'}$, the production cross section converges to a constant value given by $g_V^2 / m_{V'}^2$. The generalized Chern-Simons coupling is an effective coupling valid only below some cut-off energy, Λ . At temperatures above Λ , the production mechanism for V and V' should

^bNotice that such small electric charge escapes bounds from LEP, LHC and other searches [22] and can be as light as GeV or even lighter.

be reconsidered. This means the low energy model including V and V' should be embedded within a UV-completed model that gives rise to the generalized Chern-Simons couplings after integrating out the heavy states. The heavy sector of our model is introduced for this purpose.

The heavy sector includes chiral fermions which are electrically charged. To make the model consistent and renormalizable, V and V' are promoted as the gauge bosons of new $U_V(1)$ and $U_{V'}(1)$ symmetries. The new fermions are also charged under $U_V(1)$ and $U_{V'}(1)$ and through a triangle diagram give rise to the g_V coupling [20]. To maintain the Z_2 symmetry that protects the dark matter against decay, the new fermions are taken in the doublet representation of the $U_V(1)$ and $U_{V'}(1)$ symmetries. Assigning charges to these new fermions in a way that cancels the anomalies of the $U_Y(1) \times U_V(1) \times U_{V'}(1)$ symmetry and at the same time yields a nonzero g_V is a nontrivial exercise and requires at least two generations of heavy fermions. The Lagrangian of the new fermions in our model enjoys an accidental remnant global $U(1) \times U(1)$ symmetry that prevents their decay. Since these particles are electrically charged, we should make sure that they are not produced in the early Universe. As we have discussed in detail, this can be realized within the following two scenarios: (1) The reheating temperature is below new fermion masses. (2) The electric charges of the new fermions are too small to let them be produced.

In *summary*, our model contains two relatively light vector bosons that play the role of DM. These vector bosons couple to the photon through a generalized Chern-Simons term. This coupling produces the DM particles in the early universe within the freeze-in framework. One of the vector bosons can decay to the other boson and a photon that leads to a detectable monochromatic photon signal from galaxies and galaxy clusters. We have presented a UV-completion of the model leading to the effective Chern-Simons coupling at low energies.

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